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MATHEMATICAL MODELING OF CLIMATE CHANGE IMPACTS ON PERMAFROST DYNAMICS AND TALIK EVOLUTION

✉ *Syed Z.A.*[1], *Sherstennikova S. R.*[1, 2], *Vichare A.S.*[1], *Abbas S.*[3], *Popov S.V.*[1,2,4]

[1]St. Petersburg State University, St. Petersburg, Russia
[2] P.I. Melnikov Permafrost Institute, Siberian Branch of the Russian Academy of Sciences, Yakutsk, Russia
[3]Karakorum International University, Gilgit, Gilgit-Baltistan, Pakistan
[4] Polar Marine Geological Exploration Expedition, St. Petersburg, Lomonosov, Russia
✉ *st115941@student.spbu.ru*

This study introduces a multidisciplinary approach to assess the vulnerability of Russian Arctic permafrost to heat and mass transfer processes. Combining field data, meteorological observations, and mathematical modeling, it simulates key variables such as temperature, precipitation, snow thickness, and vegetation cover. The framework aims to enhance the accuracy of permafrost dynamics and forecasts, addressing the gap between field observations and predictive models. Focused on the Shestakovka River Basin in Central Yakutsk, it offers a robust foundation for evaluating permafrost stability under changing climate conditions.

Keywords: *Arctic, permafrost, mathematical modeling, heat exchange, hydrogeology, climate change, talik*

Introduction. Recent climate warming has profoundly issmpacted the hydrological and thermal dynamics of the Arctic and sub-Arctic regions, significantly altering permafrost conditions. The pan-Arctic basin is particularly vulnerable to these changes, which are driving the gradual degradation of permafrost. This degradation is linked to various adverse consequences, including rising ground temperatures [*Clark et al., 2015*], melting ground ice [*Daniels et al., 2015*], activation of thermokarst processes [*Gao et al., 2021*], talik formation [*Gouttevin et al., 2012*], thaw slumps [*Harris et al., 2009*], and the collapse of infrastructure [*Hegginbottom et al., 1992*]. Taliks are considered as an unfrozen ground layers of soil or rock in the permafrost zone [*Brown et al., 2002*], are commonly found in discontinuous and sporadic permafrost zones [*Cheng et al., 2012*] or in association with water bodies. However, their presence and behavior in continuous permafrost zones, particularly in Eastern Siberia, are less well understood. Continuous permafrost underlies approximately 25% of the Northern Hemisphere's land area and more than 60% of Russia [*Lebedeva et al., 2023*], with Yakutia (Sakha Republic) being entirely covered by permafrost. Although assumed spatial uniformity of continuous permafrost, localized disturbances and environmental variations often disrupt its continuity. Such features contribute to the formation of taliks, even in cold and relatively stable conditions. The climate is currently changing, and the air temperature is increasing at higher rates in the northern regions. For 1991–2020, the average air temperature in Russia has been increasing by 0.50°C per 10 years at different meteorological stations.

The study of heat and mass transfer in the upper geological layers, including talik formation, periods over half a century [*Fel'dman, 1973, 1988*]. Since the 1991s, growing concerns over climate change have intensified research on permafrost degradation and stability using numerical models based on the one-dimensional heat conduction equation in multilayer domains [*Osokin et al., 1990*]. These models often consider the influence of vegetation and snow cover on ground heat transfer [*Sosnovsky and Osokin, 2018*]. The Sosnovsky investigated soil freeze-thaw dynamics, whereas Osokin emphasized the critical moss cover thickness required for talik formation in West Spitsbergen. Recent advances also integrate theoretical insights with experimental data on water movement in frozen and thawed soils [*Fel'dman, 1988*].

Although existence of taliks is acknowledged, their distribution, formation, evolution and role in surface–subsurface moisture content (water) vegetation cover interactions remain unclear. This can be growing problem with serious implications in the balance of greenhouse gases, arctic environment ecosystems such as health of both terrestrial and aquatic as well as infrastructure stability and human activities in the arctic regions. This study investigates the Shestakovka River basin in Eastern Siberia, a representative area of continuous permafrost. By integrating field observations, meteorological data, and modeling and simulation approaches, this research aims to improve understanding of talik dynamics and their implications for permafrost dynamics and hydrogeological processes under changing climate scenarios.

Area of Study. The Shestakovka River basin covers about 170 km² and is located 20 km southwest of Yakutsk in Eastern Siberia. The area lies on the slopes of an ancient plain, with elevations between 150 and 280 meters above sea level shown in (figure 1). The permafrost here is very deep, ranging from 200 to 400 meters thick. The top 40 meters mainly consist of quartz-feldspar sands, with some layers of silty sandy loam and loam. The region has a cold and dry climate, with a mean annual air temperature is −9.5 °C. However, winters averaging −42.6 °C in January, and warm summers with an average of +18.7 °C in July. Annual precipitation is low at 245 mm, most of which (160 mm) falls during the warmer months. These conditions strongly influence the frozen ground and the natural processes in the area.

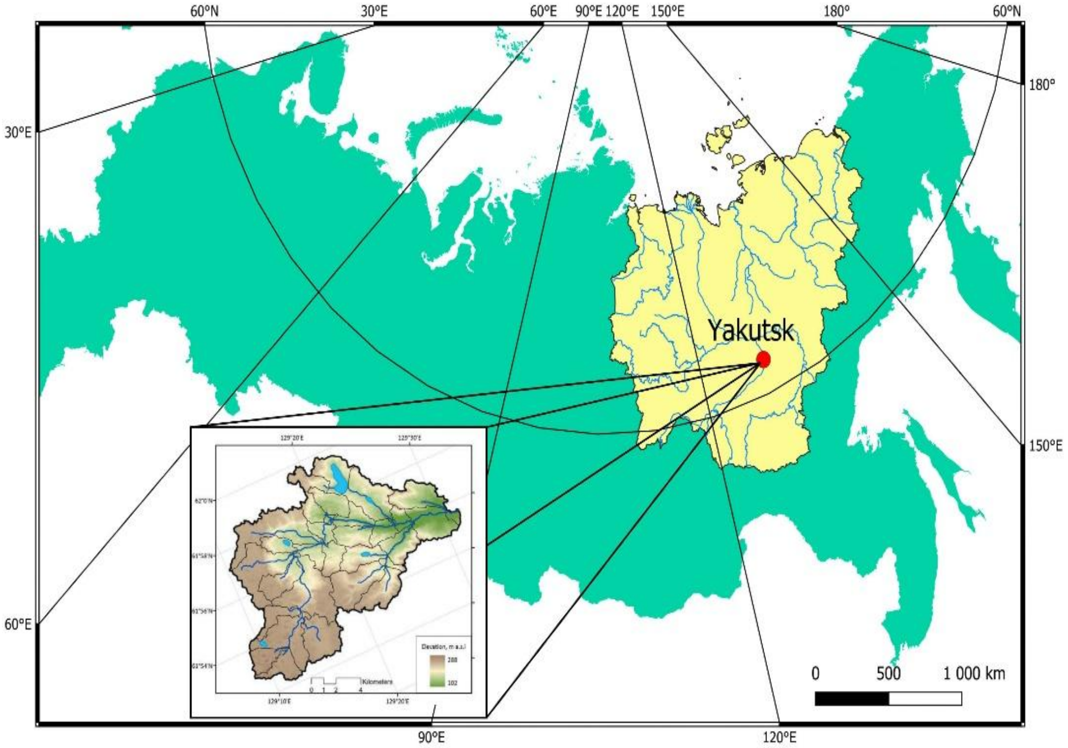

Fig. 1. Schematic map of study area Shestakovka river basin, Central Yakutia, modified from [Kaluginet al., 2020]

Model Description. Let us consider a talik as a certain horizon Ω_T, enclosed between layers of frozen or partially frozen and thawed ground. At the same time, the lower layer of permafrost Ω_P is semi-bounded. It is important to note that from the standpoint of permafrost science, the talik and the overlying seasonally frozen layer are two different areas. However, since they are part of the same sandy layer, differing only in the fact of seasonal freezing, it is expedient for the mathematical model to consider them as one when in a thawed state. Thus, within the framework of the presented model, the talik and the thawed seasonally frozen layers are combined.

Figure 2 illustrates a conceptual scheme of freezing-thawing processes in the upper part of a geological section throughout the year, characteristic of regions with perennial permafrost containing subaerial taliks. The idea behind this scheme is based on extensive observations in thermometric wells and geophysical surveys conducted in Central Yakutia [*Gagarin et al., 2019*], as well as thermal physics calculations [*Osokin, 2018*]. The scheme illustrates the model described above.

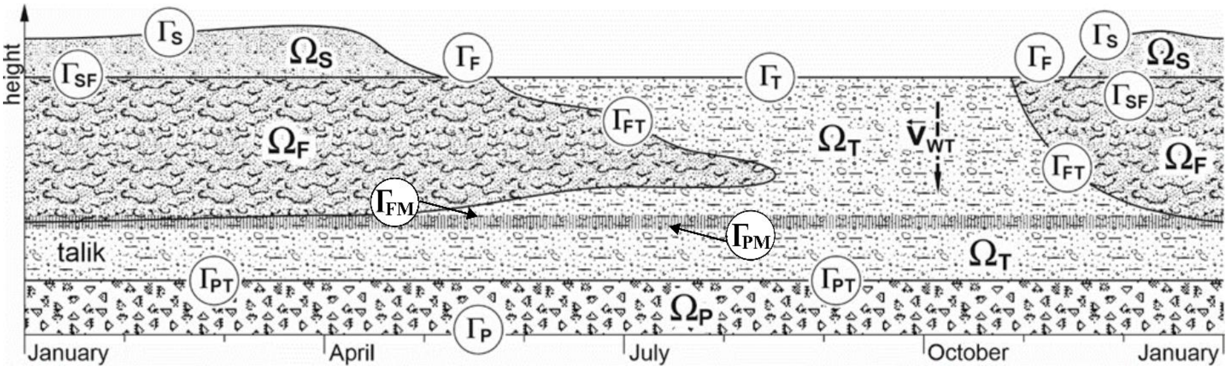

Fig. 2. Changes in the upper part of the geological section over time modified from [Popov et al.,2023]. Ω_P - permafrost rocks; Ω_F - seasonally frozen rocks; Ω_T - thawed ground; Ω_S - snow cover; Γ_P - lower boundary of the study area; Γ_S, Γ_F and Γ_T - upper boundaries of the study area; Γ_{FM} - boundary between seasonally frozen and thawed rocks; Γ_{PM} - boundary between thawed rocks and permafrost rocks; Γ_{SF} - boundary between seasonally frozen rocks and snow cover; ξ_P, ξ_S, ξ_F and ξ_T - positions of the corresponding boundaries Γ_{PT}, Γ_S, Γ_{SF}, and Γ_{FT}.

In the layer of seasonally frozen rock ΩF, during the warm season, complete or partial thawing occurs, leading to the formation of a thawed area ΩT. With the onset of cold weather, it freezes from the surface, thins, and eventually disappears. In the cold season, a snow cover ΩS forms on the ground surface, the thickness of which changes over time. As the warm season approaches, the snow gradually decreases, and eventually completely melts. Additionally, due to the warmth of solar radiation during the daytime, metamorphic processes begin to occur in the snow. The superficial layer of snow starts to melt and filter down into the depth. This gradually changes its thermo-physical parameters and density. To account for this, empirical relationships are used to calculate the effective values of thermo-physical coefficients.

Let us fix the origin at a certain depth in the layer of perennially frozen rock and direct the apical axis upwards (figure 2). The vertical position of the boundaries will be denoted by ξ with the corresponding index. If θ is the temperature of the environment, z is the current coordinate by height, and t is the time, then the description of the heat-fluid transfer process in the enthalpy formulation can be represented by the following equation:

$$\rho_\Delta c_\Delta \frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_\Delta \frac{\partial\theta}{\partial z}\right) + v_{WT}\frac{\partial\theta}{\partial z} + \Phi, \qquad z \in \Omega_W, \Omega_I, \Omega_S, \Omega_T, \Omega_F, \Omega_P \qquad (1.1)$$

where ρ_Δ, c_Δ, and λ_Δ are the smoothed parameters of the medium: density, specific heat capacity, and thermal conductivity. This is a known technique, and this representation allows replacing Stefan's boundary conditions with thermophysical parameters of a special form, which significantly simplifies further numerical solution. Then

$$\rho_\Delta = \begin{cases} \rho_j(\theta), |\theta-\theta^*| > \Delta\theta^* \\ \rho^*(\theta), |\theta-\theta^*| \le \Delta\theta^* \end{cases}, \quad c_\Delta = \begin{cases} c_j(\theta), |\theta-\theta^*| > \Delta\theta^* \\ c^*(\theta), |\theta-\theta^*| \le \Delta\theta^* \end{cases}, \quad \lambda_\Delta = \begin{cases} \lambda_j(\theta), |\theta-\theta^*| > \Delta\theta^* \\ \lambda^*(\theta), |\theta-\theta^*| \le \Delta\theta^* \end{cases},$$

where the index j corresponds to the index of one of the areas Ω_W, Ω_I, Ω_S, Ω_T, Ω_F, or Ω_P, and ρ^*, c^*, and λ^* are the parameters in the narrow zone $\Delta\theta^*$ of temperatures θ near the phase transition temperature θ^* for the phase boundaries Γ_{PT}, Γ_{FT}, and Γ_{WI}. In calculations, it should be kept in mind that the value of θ^* depends on the pressure P: $\theta^* = K_0 - PC^*$, where C^*=7.43 K/GPa, and K_0 = 273.15°C [*Paterson, 1994*].

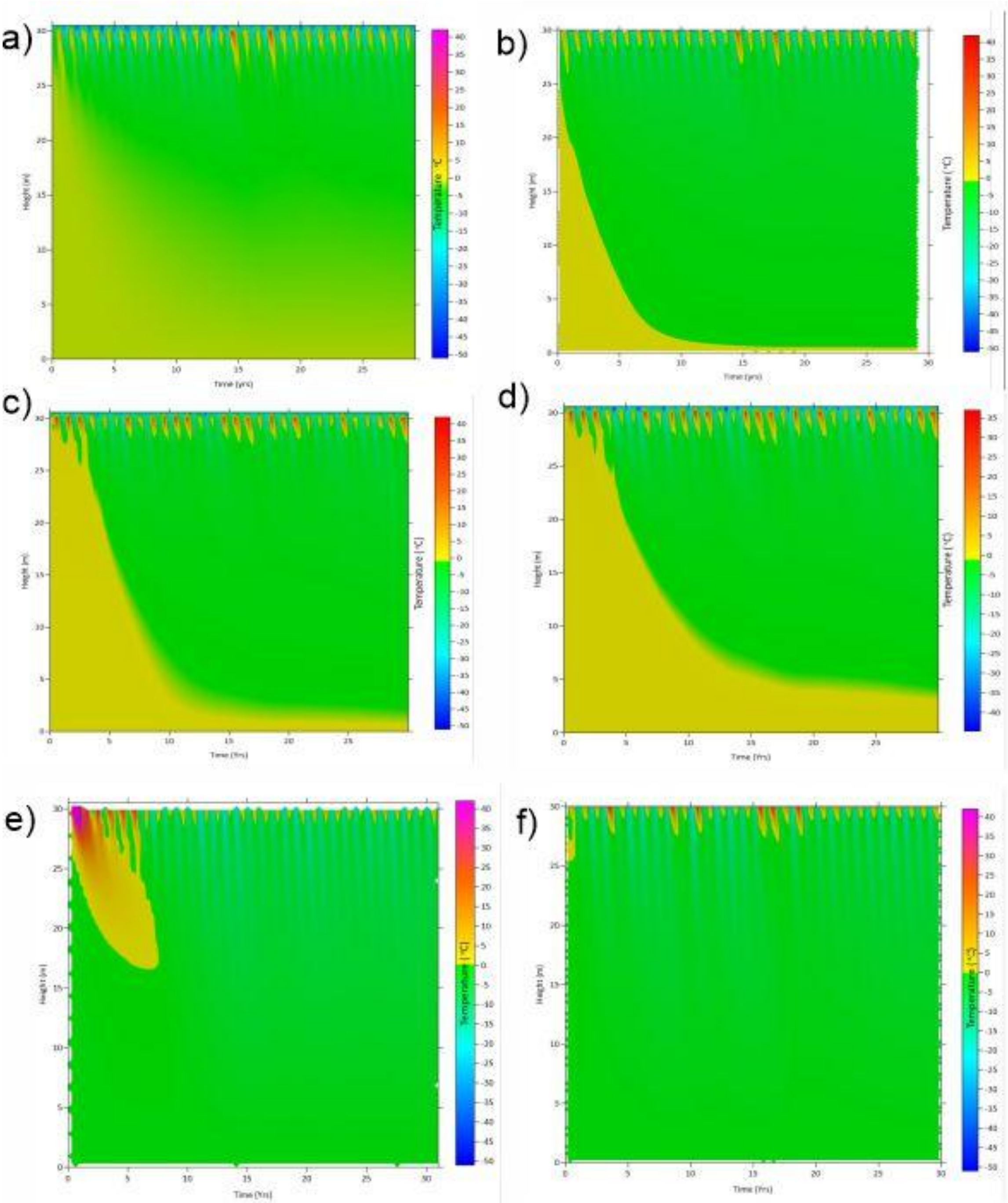

Fig. 3. Result of modeling of ground temperature with various scenarios (a) 20% moss - 5% moisture, (b) 10% moss - 5% moisture, (c) 20% moss - 20% moisture, (d) 10% moss - 20% moisture, (e) without moss - 5% moisture and (f) without moss - 20% moisture.

Results. The simulations results reveal the impact of moss cover and soil moisture on permafrost dynamics under varying environmental scenarios. The following observations can be made from the results:

Role of Moss Cover:

Moss significantly insulates the permafrost, maintaining cooler temperatures in the subsurface. Figure 3(a) and (c), which feature 20% moss cover, show lower temperatures compared to scenarios with reduced or no moss (b, d, e, f). Thicker moss layers reduce the extent of permafrost degradation over time, highlighting its protective role.

Impact of Moisture Content:

Higher moisture levels (20%) result in greater heat transfer and accelerated thawing of the permafrost. Figures 3(c) and (d) demonstrate faster warming and talik formation compared to lower-moisture scenarios (a, b). This effect is further amplified in the absence of moss cover, as shown in Figures 3(e) and (f), where significant permafrost thaw is observed.

No Moss Cover:

Without moss cover, the permafrost is highly vulnerable to thawing, particularly under low-moisture conditions. Figure 3(e) shows rapid talik development starting early in the simulation, whereas Figure 3(f) highlights even deeper thaw in high-moisture conditions. These findings suggest that moss acts as a critical buffer against warming, especially in drier conditions.

Interaction between Moss and Moisture:

The combined effect of moss and soil moisture determines the rate and extent of permafrost thawing. Higher moss cover and lower moisture content are optimal conditions for maintaining permafrost stability, while scenarios with reduced moss or increased moisture leads to accelerated thawing and talik formation.

Conclusion. The simulations highlight the critical role of moss cover and soil moisture in governing permafrost dynamics. Moss acts as a natural insulator, significantly reducing ground temperature fluctuations and delaying permafrost degradation. Conversely, higher soil moisture levels intensify thermal conductivity, accelerating thawing and talik formation, particularly when moss is absent. Scenarios with both dense moss cover and low soil moisture demonstrate the greatest resilience to warming, while reduced vegetation or higher moisture levels lead to pronounced thaw depths. These results emphasize the need to prioritize vegetation conservation and consider soil hydrology in predicting permafrost responses to environmental change.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ВОЗДЕЙСТВИЯ ИЗМЕНЕНИЯ КЛИМАТА НА ДИНАМИКУ ВЕЧНОЙ МЕРЗЛОТЫ И ЭВОЛЮЦИЮ ТАЛИКА

Сайед З.А.[1], Шерстенникова С.Р.[1,2], Вичаре А.С.[1], Аббас С.[3], Попов С.В.[1,2,4]

[1] СПбГУ, Санкт-Петербург, Россия
[2] Институт мерзлотоведения им. П.И. МельниковаРАН, Якутск, Россия
[3] Каракорумский международный университет, Гилгит, Гилгит-Балтистан, Пакистан
[4] Полярная морская геологоразведочная экспедиция, Санкт-Петербург, Ломоносов, Россия
st115941@student.spbu.ru

В этом исследовании представлен междисциплинарный подход к оценке уязвимости вечной мерзлоты Российской Арктики к процессам тепло- и массопереноса. Объединяя полевые данные, метеорологические наблюдения и математическое моделирование, он моделирует ключевые переменные, такие как температура, осадки, толщина снега и растительный покров. Целью этой модели является повышение точности динамики вечной мерзлоты и прогнозов, устраняя разрыв между полевыми наблюдениями и прогностическими моделями. Сосредоточенный на бассейне реки Шестаковка в Центральной Якутии, он предлагает надежную основу для оценки устойчивости вечной мерзлоты в условиях изменения климата.

Ключевые слова: *Арктика, вечная мерзлота, математическое моделирование, теплообмен, гидрогеология, изменение климата, талик*